MULTI-ROBOT GUIDED AUTONOMY FOR INDOOR EXPLORATION

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ABSTRACT

The effective use of multiple Unmanned Ground Vehicles (UGVs) in an indoor environment can be challenging due to the several environmental and technical constraints. It becomes more challenging when a single operator is required to manage more than one UGV. Hence, there is a need to look into how this can be effectively addressed and to develop the necessary approaches to testing and selecting the solutions. One approach is to develop guided autonomy capabilities to reduce the amount of operator interaction.

This paper presents work done to develop a system to provide multi-robot guided autonomy for enhancing the performance in indoor exploration. The general focus of the effort was to design an Operator Control Unit (OCU) with Human-Robot Interaction (HRI) considerations to address operator loading issues as well as waypoint navigation and obstacle avoidance capabilities to enable guided autonomy. The system was design to allow a single operator to manage two UGVs. User trials were conducted throughout the development phase to iteratively improve the designs. The results were promising and future work will look at developing task-level autonomy to further reduce operator workload and enhancing OCU interface design for operational use.

1. INTRODUCTION

In recent years, there has been an increase in the use of mobile robots for urban operations in order to reduce the risk to human life and enhance the soldier's capabilities. However, their control is still largely via tele-operation, which requires intensive training for effective operator control. There is a growing interest to provide autonomy to such robots and to date, one of the most notable autonomous robot work for urban operations using man-portable robots is by iRobot Corporation (Yamauchi, 2005; Jones and Lanser, 2006), though their applications have yet to transit to operational usage. In fact, operational use of autonomous Unmanned Ground Vehicles (UGVs) has been severely lagging behind systems from other domains such as Unmanned Aerial Vehicles (UAVs).

A possible reason for this is that there are several challenges in using UGVs for urban operations. In an indoor environment, the number of challenges increases tremendously. Unlike the outdoor environment, the indoor environment may be structured but can also be cluttered. Navigating in a cluttered scenario can increase the workload and reduce the attention capacity of the UGV operator. This is further exacerbated when coping with poor localization, facing communications issues due to the building structure, and dealing with time constraints of an operation. If another UGV is added for the operator to control, the efficiency of the operator will definitely be compromised. Monitoring the UGVs can be further hampered by the limited screen-size of the Operator Control Unit (OCU).

To tackle such operator workload issues, one approach is to provide guided autonomy capabilities to the UGVs to ensure their operations require reduced amounts of operator interaction. This paper will present work done to develop such a system. The system is designed to allow a single operator to control two UGVs simultaneously and remotely via a static OCU. The OCU interface design is one of the key focuses of this effort, taking into account Human-Robot Interaction (HRI) considerations to improve the operator's efficiency. To aid the development of future work, the hardware and software payloads have been carefully designed to be robotic platform-independent. The system has been designed to address the reconnaissance needs during Chemical, Biological, Radioactive, and Explosives (CBRE) operations and this has served to further focus the developmental efforts. Key operations include exploring unknown indoor environments, mapping such areas, and marking locations of objects of interest in the constructed map.

Section 2 presents an overview of the system and its major components, focusing on the robotic platform-independent payload. Section 3 moves on to further describe the OCU interface design which was critical in enabling the control and monitoring of two UGVs. Section 4 summarizes some of the results obtained from tests and user trials. Finally, the paper concludes with a summary of some of the key findings, the lessons learnt, and a preview of potential future work.

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2. SYSTEM OVERVIEW

The system consists of two UGVs and one static OCU. The overview of the system is illustrated as a block diagram in Fig. 1. The two UGVs have the same internal components to ensure that their payloads are able to be robotic platform-independent. The main exception is the Actuator component which differs slightly as it is the platform abstraction layer.

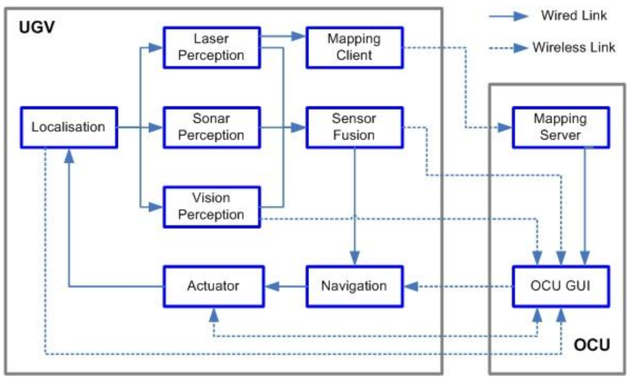

Fig. 1: System block diagram

Each Perception component independently processes its own sensor data and outputs a cost grid. The Sensor Fusion component generates a combined cost grid suitable for navigation. The Navigation component uses this to carry out autonomous waypoint navigation and obstacle avoidance. The Actuator component then controls the robotic platform accordingly and provides feedback to allow the Localization component to determine the UGV pose. The Mapping components work together to combine the local map data from the two UGVs into a high fidelity map on the OCU. The OCU Graphical User Interface (GUI) provides videos, maps, and status information for the operator to monitor the UGVs. It allows the UGVs to be controlled via tele-operation using a joystick or semi-autonomous mode using waypoints. The overall system's middleware is developed with reference to the Joint Architecture for Unmanned Systems (JAUS) standard (JAUS, 2007).

To support the processes of these components, each UGV has two Pentium-M 1.8GHz PC/104 computer stacks. The OCU utilizes a 17-inch widescreen laptop which provides sufficient screen space for the OCU GUI. Communication between the UGVs and the OCU is achieved using Rajant BreadCrumb ME2 radios which integrate Ethernet and wireless 802.11b/g connectivity with mesh networking protocols. This has been adequate to meet the range and bandwidth requirements. The robotic platform-independent payload has been successfully tested and demonstrated on an iRobot PackBot Scout and a MobileRobots Pioneer P3AT as shown in Fig. 2 and Fig. 3 respectively.

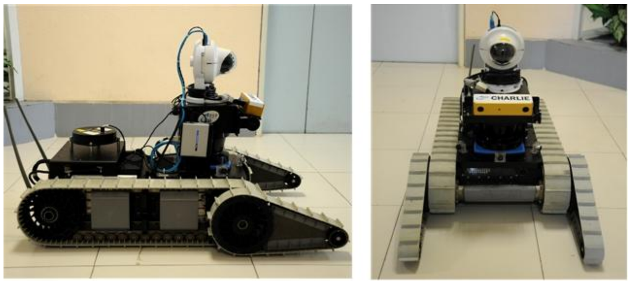

Fig. 2: Payload on an iRobot PackBot Scout

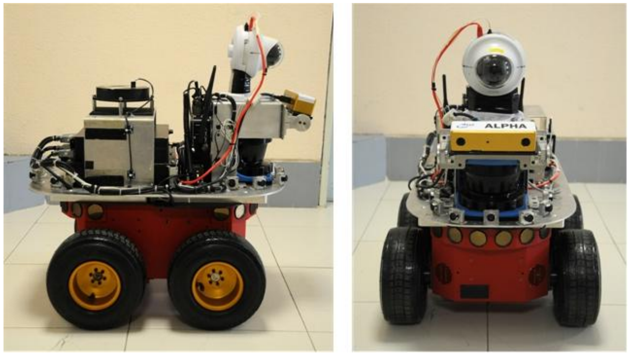

Fig. 3: Payload on a MobileRobots Pioneer P3AT

2.1 Perception Components

Perception consists of three different sensing components, each providing a 8m by 8m cost grid which is then fused together to give a better awareness of the obstacles surrounding the UGV. The three sensing components are the Laser Perception, Sonar Perception, and Vision Perception components. Each sensing component provides obstacle information that complements the others. The Sensor Fusion component is responsible for combining the cost grids from these sensing components for use by the Navigation component.

The Laser Perception component receives laser range measurements from a SICK Laser Measurement Systems 200 (LMS 200) unit for a high fidelity 180-degree planar view of the environment. It operates at 10Hz. The laser has the longest sensing range and is the primary component for perception. In addition to the cost grid provided for navigation, it provides information to the Mapping Client component for constructing local maps, necessary for constructing the merged map on the OCU.

The Sonar Perception component uses an array of MaxBotix MaxSonar-EZ1 Ultrasonic Ranger Finders to complement the laser. It operates at 2Hz. The ultrasonic sensors do not provide the laser's level of accuracy but unlike the laser, they are capable of detecting glass and mirrored surfaces. The operator can continue to command the UGVs without having to be concerned with such obstacles. Fig. 4 shows a scenario where the UGV is

faced with glass doors which it detects and avoids successfully.

Fig. 4: Sonar perception used to avoid glass obstacles

The Vision Perception component uses a Point Grey Research Bumblebee stereo vision camera for detecting small and negative obstacles. It operates at 4Hz. This camera complements the ultrasonic sensors and laser as it is tilted down to focus in the region below the scanning plane of the laser and the scanning height of the ultrasonic sensors. Small obstacles such as boxes, trash bins and steps cannot be driven over and negative obstacles such as downward stairs can cause the UGV to fall into an irrecoverable situation. By detecting such obstacles, the operator can pay less attention to the UGV's surroundings and attend to more critical tasks. This helps to improve the operator's situation awareness. Fig. 5 shows a scenario where the UGV is faced with downward stairs which it detects and turns away successfully, refusing to proceed any further.

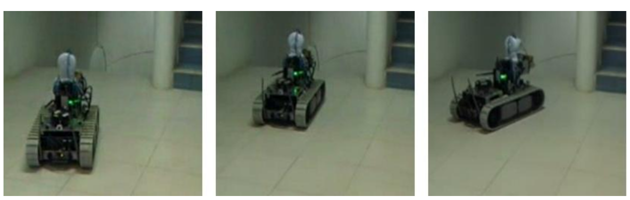

Fig. 5: Vision perception used to avoid stairs

The stereo vision camera also doubles as the drive camera, providing the operator with a view of the area directly in front of the UGV. In addition to the stereo vision camera, the Vision Perception component has a Sony SNC-P5 network camera. The primary purpose of this network camera is to improve the situation awareness for the operator by providing Pan-Tilt-Zoom (PTZ) capability which is able to operate independent of the UGV's heading.

The Sensor Fusion component takes the three sensor cost grids and forms a combined 8m by 8m cost grid to provide a coherent representation of the local environment. The fusion algorithm uses the sonar cost grid as provided but the laser and vision cost grids have to undergo temporal fusion due to their limited field of views. The resultant cost grid is then passed on to the Navigation component.

2.2 Navigation Component

The Navigation component provides the autonomous waypoint navigation and obstacle avoidance capabilities. The Vector Field Histogram (VFH) algorithm (Borenstein and Koren, 1991) was initially selected for this component. However, the implementation did not perform well at speeds close to 1m/s and was also prone to problems associated with local minima. Subsequently, the Obstacle-Restriction Method (ORM) algorithm (Minguez, 2005) was adopted and it has performed better at higher speeds of up to 1.2m/s. Fig. 6 shows a scenario where the UGV is carrying out obstacle avoidance at a speed of 1m/s.

Fig. 6: Obstacle avoidance at 1m/s

To reduce the complexity of this component, it only focuses on local navigation with the bounds of the perception cost grid and is deliberately not given access to the overall map representation of its surroundings. As the overall merged map from the two UGVs resides only in the OCU, path planning takes place in the OCU after which waypoints are sent to the Navigation component for execution. The A* algorithm was sufficient to meet the requirements for path planning in the OCU. To further reduce the component's complexity, the robotic platform is assumed to be skid-steered and hence, the current component implementation is not suitable for all kinds of robotic platforms.

2.3 Actuator Component

The Actuator component interfaces the robotic platform to send raw motion commands and retrieve platform status information such as odometry data and battery strength. This component abstracts the complexities of the interface from the rest of the system and is the main component to be modified when another robotics platform is introduced. It interfaces the Pioneer P3AT via a RS232 serial link while it interfaces the PackBot Scout via an Ethernet link at its paybreak interface. Safety mechanisms have been introduced in this component. One safety feature is to limit the maximum speed and turn rate. Another safety feature is to require a stream of control messages for the component to operate. If the stream is disrupted for any reason, the component applies the brake immediately.

2.4 Localization Component

The Localization component is responsible for providing the pose information of the UGV. It utilizes data from the robotic platform's odometry and a Fizoptika VG-035 fiber-optic gyro. The odometry data provides the translational information while the gyro provides the rotational information. The gyro complements the odometry as odometry is more prone to rotational errors than translational errors. Fig. 7 shows the effects of localization with and without the gyro on map data. It is clear that rotational errors have been effective reduced but translational errors still exist due to odometry errors.

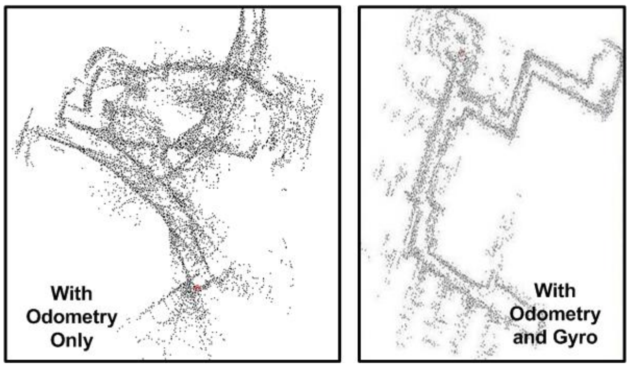

Fig. 7: Localization with and without gyro

2.5 Mapping Components

The Mapping components work together to construct a two-dimensional map of the environment that the UGVs are exploring. They comprise of the Mapping Client and Mapping Server components. This merged map is also used for path planning to find a suitable route when the operator specifies a desired waypoint anywhere on the map.

The Mapping Client component regularly generates small local maps by collecting and processing Laser Perception data, which has the highest accuracy. Each time a local map has been built over pre-defined time and distance, it is transmitted over to the Mapping Server component that resides on the OCU. If the transmission is successful, the local map is partially discarded. This approach serves to limit the memory consumption for processing the local map and reduce the bandwidth requirements for sending the local map to the OCU.

The Mapping Client component on each UGV builds its local maps by using a particle filter-based Simultaneous Localization and Mapping (SLAM) algorithm, which is a modified version of Distributed Particle SLAM (DP-SLAM) (Eliazar and Parr, 2006). The Mapping Server component constructs an overall map by using a map merger technique for occupancy grid maps (Birk and Carpin, 2006). To simplify the map merging process, it is assumed that the UGVs start in close proximity. This hybrid approach to map management allows for easier scaling up to more UGVs. Fig. 8 shows the resultant merged map on the OCU after receiving multiple local maps from two UGVs.

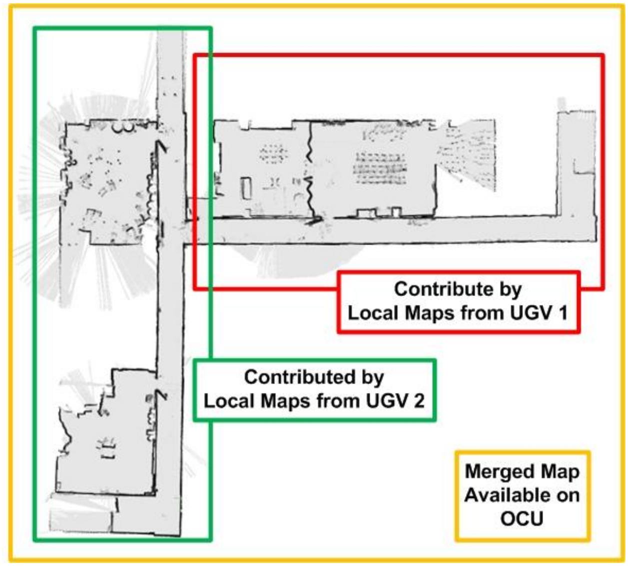

Fig. 8: Map merging

3. INTERFACE DESIGN

The interface design was developed based on the User Centered Design (UCD) process (Adams, 2002) which consists of two phases. The first phase is to gather user requirements and the second phase is to design and refine the interface.

In the first phase, the Goal-Directed-Task Analysis (GDTA) technique (Endsley et al., 2003) was applied to identify the user requirements after which human factors and design rules were employed to guide the preliminary interface design. This design focused on single UGV control to first firm up all the necessary controls and screen information required.

With the preliminary interface design user trials were conducted to obtain feedback on the interface usability. The design phase and user trials were iterated until a prototype interface design for two-UGV control was obtained as shown in Fig. 9. The process was further iterated until a final interface design was obtained as shown in Fig. 10. The layout of the interface design is as shown in Fig. 11.

The controls and status information of two UGVs are color-coded and have mirrored-image layouts to easily differentiate them. All buttons have tool tips to enable easy identification of their functions.

Fig. 9: Screenshot of prototype interface design

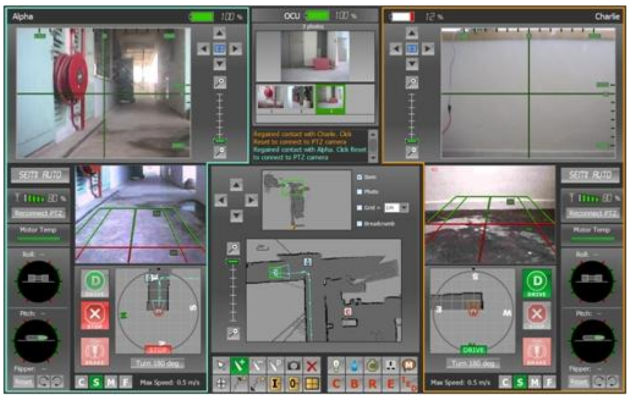

Fig. 10: Screenshot of final interface design

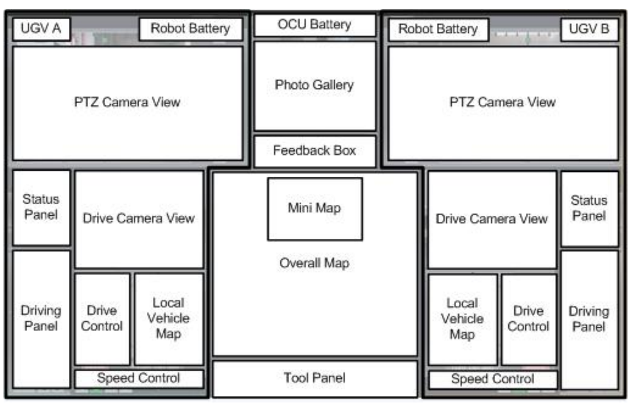

Fig. 11: Layout of final interface design

The battery status of each UGV is displayed at the top of the interface. The PTZ camera view shows the video stream from the PTZ camera with lines overlaid to highlight the current pan and tilt angles. The status panel displays the UGV's current mode of operation which can be tele-operation or semi-autonomous. The drive camera view shows the video stream from the stereo vision camera with lines overlaid to provide depth perception. The driving panel shows the pitch, roll, and flipper angle if available. The drive control allows the operator to put it in drive or stop mode as an override feature during semi-autonomous operation. The local vehicle map shows the current local map of the UGV with the UGV in the middle of the map, facing north. A rotating compass is overlaid to show the heading of the UGV. The operator can click in the local vehicle map to specify a waypoint for the UGV to drive to. The speed control allows the operator to select from four different pre-defined speeds.

The battery status of the OCU is displayed at the top of the interface as well. The photo gallery shows photos that have been taken by the operator. When a photo is selected, the location and direction of the previewed photo is highlighted in the overall map. The feedback box displays messages to report events such as lost of communications or path planning progress. The overall map displays the map constructed by merging the local maps from the UGVs. The operator can select a UGV by clicking on its symbol and click in the overall map to specify a waypoint for the selected UGV to drive to. The map also displays grid lines for distance measurements, marked locations of items of interest, and locations of photos taken. The mini map within the overall map serves to show the entire merged map at all times as the overall map can be zoomed in and out. The tool panel contains tools for managing waypoints, marking items of interest, and taking photos.

4. TRIALS AND RESULTS

Trials were an integral part of the developmental process of this work. One such trial setup is as shown in Fig. 12. Several red boxes have been placed in a single storey indoor environment and a military operator is tasked to search, identify, and annotate the red boxes in the map. The operator is given some time to familiarize with the controls before the trial begins. During the trial, the operator is videotaped for post-trial analysis. After the trial, the operator is interviewed by human factors engineers for feedback on the interface usability. The performance and feedback results are evaluated and revisions are made to both the interface design and UGV controls iteratively.

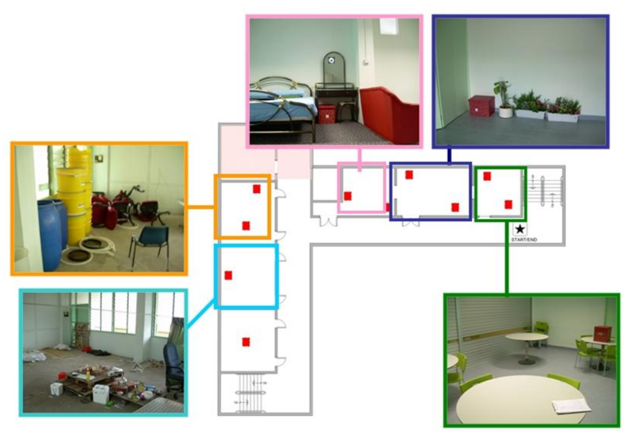

Fig. 12: Typical trial setup

The trials were invaluable in identifying the deficiencies and tackling them swiftly. The trial results were promising as the interface design enabled the operators to learn its control quickly and they were able to perform their tasks in the trials without major issues. The operators rated the interface favorably in questionnaires and commended its features, especially the photo-taking capability.

One finding from the trials was the difficulty of simultaneous control of two UGVs during high concentration tasks such as identification of objects of interest. This resulted in situations where the operator would be focused on one UGV while neglecting the other UGV. However, it was also observed that simultaneously controlling the two UGVs via waypoints was easier to manage. This would suggest a need for high levels of autonomy where tasks such as identification and exploration can be managed by the UGVs and operator's input is requested only when necessary.

Another finding was the impact to performance due to false positives when detecting small negative obstacles. Highly reflective surfaces and repetitive floor patterns often triggered false positives, preventing the UGV from advancing. This in turn resulted in the operator switching to tele-operation mode in order to overcome the situation.

Other findings include issues with localization and map merging which affected the performance of path planning in the overall merged map. The number of messages displayed in the OCU was also highlighted as it can be easily missed by an operator due to information overload.

One test done outside the scope of the user trials was stair-climbing. Care was taken to ensure the load and balance of the PackBot Scout was managed. The UGV was still able to descent and ascent a flight of stairs via tele-operation as shown in Fig. 13. This however could not be sustained for a long period of time as the payload weight put a strain on the battery capacity.

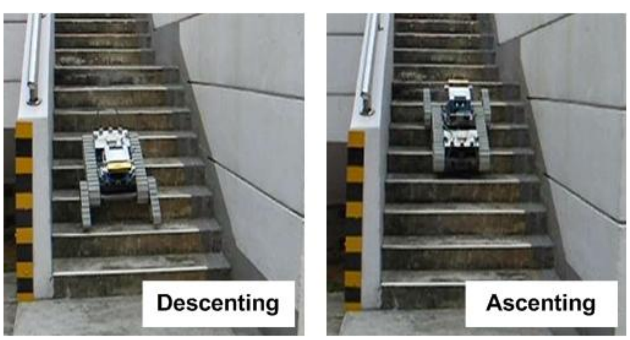

Fig. 13: Stair-climbing

CONCLUSIONS

The work has demonstrated the capability for a single operator to control two UGVs in a constrained indoor environment. The operator is able to carry out and complete the allocated tasks. The system has shown potential to be a valuable asset to the CBRE forces during their reconnaissance operations, allowing them to conduct their operations from a safe distance. The system has also allowed for a better understanding of the issues related to multi-robot control. From the frequent switching of attention between the two UGVs, it is clear from the trials that more work is needed to increase the level of autonomy so that it can further enhance the operator's performance. The ability of the UGV to perform more tasks without frequent human intervention will definitely contribute to increasing the benefits of multiple robots operation. There is also a need to address the sensing capabilities to reduce the occurrence of false positives in sensor data.

Future work will look into developing task-level autonomy to further reduce the operator's load. Features such as autonomous exploration and mapping can serve to allow the operator to spend more time observing the video feedback and status information. Other areas to look at will be in enhancing the OCU interface design by taking into account more operational considerations. Considerations include reducing the OCU screen size, improving situation awareness, designing for mobile operation, and running trials with a larger pool of military operators.

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